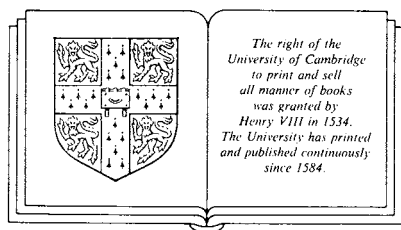


Flow and reactions in permeable rocks

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE

NEW YORK PORT CHESTER MELBOURNE SYDNEY

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
40 West 20th Street, New York, NY 10011, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

© Cambridge University Press 1991

First published 1991

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data

Phillips, O. M. (Owen M.), 1930–

Flow and reactions in permeable rocks/O.M. Phillips.
p. cm.

ISBN 0-521-38098-7

1. Fluid dynamics. 2. Rocks – Permeability. I. Title.

TA357.P48 1991

90-44208

552 – dc20

CIP

British Library Cataloguing in Publication Data

Phillips, O. M. (Owen Martin) 1930–

Flow and reactions in permeable rocks.

1. Hydrology

I. Title

551.48

ISBN 0-521-38098-7

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1 Introduction

It has been evident since the days of James Hutton in the late eighteenth century that this solid earth has been in upheaval throughout a history longer than could easily be visualized. Recurrent and overlapping cycles of igneous intrusion and deposition, deformation and folding, with erosion by air and water, redistribution and sedimentation have shaped the surface of the earth and hinted at great tectonic forces within. The grandeur of the canvas painted by geology, the science of the earth, has excited the imagination of those who have the capacity to wonder and has drawn in the talents of biologists, physicists, and chemists such as Darwin, Rayleigh, Jeffreys, Elsassner, Urey, and many more in the preceding century and this. New discoveries in the basic sciences and new techniques of observation have again and again revolutionized our view of the earth – it has been barely twenty years since measurement of magnetic anomalies over midoceanic ridges forced the acceptance as reality of the process of sea-floor spreading leading to continental drift, a notion previously regarded as close to heresy.

But no more. Abundant evidence now indicates that the crust of the earth is spreading from the midocean ridges that gird the globe and is disappearing in the subduction zones of the deep ocean trenches carrying the continental blocks in a grandly and gradually changing pattern. Deep-mantle convection is presumably responsible, with material solid enough to transmit seismic S-waves behaving also as a gradually deforming fluid. The worldwide distribution of volcanism is intimately associated with these tectonic motions. In recent years, the fluid behavior of magmas, igneous intrusions, and melts has drawn the attention of such imaginative and powerful scientists as Herbert Huppert, Dan McKenzie, and Stewart Turner, and this field is sparkling with new ideas.

As applications of physics and chemistry brought new insights to geology, they also posed new questions. The development of geochemistry in the past fifty years has led to the clarification of many aspects of metamorphism, the term used to describe the transformation of minerals from one form to another at depth under conditions of high temperature and pressure. Volatiles may have had to escape so that the reaction would not reverse itself, but there has been plenty of time to accomplish this. Yet a number of mysteries remain. Natural processes are, in the large, dispersive, as the second law of thermodynamics insists. How is it that local

concentrations of minerals aggregate deep inside the earth, leading to the accumulation of economically valuable resources? The Mississippi Valley lead–zinc deposits were clearly formed after the lithification of the host rock, but where did they come from, how did they get there, why did they deposit where they did and not somewhere else? The dolomitization of limestone requires the importation of large quantities of magnesium; in these and other geochemical processes there is an evident need to account for the transport of minerals, presumably dissolved, through existing assemblages in quantities much larger than can be associated with compaction of a fluid-saturated matrix and at rates much faster than can be produced by diffusion. No reader of Francis Pettijohn's *Sedimentary Rocks* can remain unaware of the puzzle, but only fairly recently has the idea gained acceptance that these chemical transports must be associated with fluid flow through rocks that a hydrologist may consider hardly permeable, over time intervals of millions or hundreds of millions of years. When pressure or buoyancy forces are present, the latter usually associated with temperature gradients, interstitial fluid may flow through the matrix if it is reasonably permeable or along cracks and fractures if it is less so. What are the large-scale and small-scale patterns of flow? In which direction does the fluid move, how fast, where from, and where to? What governs the distributions of reaction, of dissolution, and of deposition that, over eons, led to the distributions of mineralization that we see today?

The search for answers to these questions involves a combination of structural geology, which defines the geometry and characteristics of the matrix; geochemistry, which specifies the nature of the reactions that can occur; and fluid mechanics, which governs the flow and transport of dissolved chemicals from one place to another. The fundamental rules of fluid percolation through rocks or other permeable media have been known since Darcy's time, but the variety of flow patterns in geological structures and their textural and geochemical consequences are far from having been fully explored. The ranges of pertinent parameters are often extreme – the permeability of an evaporite bed may be ten orders of magnitude smaller than that of a gravel bank. Even in one material, limestone, field measurements may indicate a permeability five orders of magnitude larger than that inferred from laboratory samples because of mesoscale fracturing or dolomitization. Chemical reactions may proceed almost instantaneously or take thousands of years to approach equilibrium. In many instances, the appropriate parameters are simply not known even to an order of magnitude, and this provides an opportunity and a trap – an opportunity in that careful analyses of the consequences of flow can reduce or place limits on the uncertainty, and a trap in that one can often “pick a number” within a wide range to give any desired numerical agreement.

Even the basic three-dimensional geometrical structure of a basin is

seldom known precisely. Much of the information in structural geology has been derived from two-dimensional exposures and surficial mapping. Drilling is expensive and cores give only widely separated vertical traverses. The techniques of seismic reflection now make it possible to obtain much greater detail, though even in well-explored regions, the disciplined imagination of the structural geologist is still a necessity. The difficulties are compounded as we reach farther into the past. Not only have the geological structures evolved with the relentless sequence of tectonic upheaval, erosion, and deposition, with the consequent evolution of the patterns of flow, temperature, and pressure, but also the physical and chemical nature of the rocks themselves has changed with metamorphism, dissolution, and cementation. The correct interpretation of these changes requires all the skill of the geochemist and the petrologist, and an appreciation of the influence of interstitial flow is but one of the tools that must be employed. It is an important one, though; flow provides fluxes of chemical species, slow but enduring throughout geological time, that allows reactions to continue and petrological changes to accumulate.

It is not the purpose of this book to construct a detailed model of the flow-associated changes that have occurred in any particular basin or other geological structure, but rather to develop, from the basic physical and chemical balances, a set of derived or secondary rules that can guide geological interpretation in a variety of contexts. We seek associations among the general characteristics of geological structures, the characteristic patterns of flow that they allow, and the patterns and rates of physical and chemical changes that occur as a consequence and are reflected in the distributions of mineralization. A number of examples that exhibit these connections are given, but they are far too few. Ideally, a development such as this would be guided by geochemical flow experiments in permeable media, but this would require extrapolation from achievable laboratory flow rates, time scales, temperatures, and pressures to those that occur deep in the earth over millions of years. A number of important experiments by Elder and others, however, have illustrated aspects of convective flow patterns in some simple geometries. The art of numerical simulation of basin-wide flow, temperature, and reaction patterns has developed rapidly in recent years, notable contributions having been made by Garven and his collaborators, but these inevitably require a specific configuration and choice of the numerical values of the parameters involved; it is not always clear how specific features of the solution depend on these choices. The results presented here can, nonetheless, provide insights by relating these features to the local or overall flow characteristics. The two approaches are, indeed, complementary. A conceptual framework elucidating the relations among flow characteristics, driving forces, structure, and reaction patterns enables us not only to understand the results of numerical modeling more clearly, but to check them. (Nu-

merical calculations *can* converge to a grid-dependent limit, and artifacts of a solution *can* be numerical rather than geological.) Numerical modeling provides a quantitative description and synthesis of a basin-wide flow in far greater detail than would be feasible analytically. The combination of the two techniques is a much more powerful research tool than either alone.

In the next chapter are specified the general geometrical characteristics and basic physical and chemical balances that underlie the developments in the remainder of the book. These are the rules by which the game is to be played, but within these rules, many kinds of play are possible. Chapters 3 and 4 develop a variety of these and illustrate the closeness of the relationships among structure (the distribution and characteristic geometry of permeability variations), flow within the structures, and distributions of chemical reactions of several types associated with this flow. When the interstitial fluid viscosity is uniform and buoyancy effects are negligible, the flow solutions are unique, but if temperature or salinity variations are significant, a given initial distribution may be dynamically unstable and evolve into some other. Some conditions for stability or instability are illustrated in Chapter 5 by typical geological examples. The two great driving forces for large-scale circulations through rocks are pressure differences, hydraulically induced, and variations in basement temperature or heat flux; their flow, thermal, and mineralogical signatures are described in the last two chapters, again by means of several examples in which direct observations or numerical experiments are sufficiently complete to make comparison possible. One again laments that there are not yet enough examples such as these; it is to be hoped that in future years more will become available to provide support (or otherwise) for existing results and point in new directions. Only thus can this area of geology advance.